2002

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Lyα ABSORBER CORRELATIONS AND THE "BIAS" OF THE Lyα FOREST

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Abstract Lyα absorber correlations contain information about the underlying density distribution associated with a particular class of absorbers. As such, they provide an opportunity to independently measure the "bias" of the Lyman alpha forest, i.e. the relationship between H I column density and underlying dark matter density. In these proceedings we use hydrodynamic simulations to investigate whether the evolution of this bias is measurable from observable correlations. Unfortunately, the increasingly complex physics in the IGM at $z \lesssim 1$ makes a direct measurement of the bias difficult. Nevertheless, current simulations do make predictions for H I absorber correlations that are in broad agreement with observations at both high and low redshift, thus reinforcing the bias evolution predictions given by these models.

Recent results indicate that hydrodynamic simulations provide an accurate description of the local intergalactic medium as traced by weak ($N_{\rm HI} \lesssim 10^{14}{\rm cm}^{-2}$) Ly$\alpha$ absorption lines (e.g. Davé & Tripp 2001). A key free parameter in such models is the "bias" of the Lyα forest, i.e. the relationship between the column density of a given absorber and the density of the underlying dark matter associated with that absorber. (Since pressure forces are typically small at the low densities and temperatures in the diffuse IGM, local dark matter and baryon densities trace each other very well.) At high redshifts ($z \gtrsim 2$), there is a tight relationship between these quantities (Hui & Gnedin 1997; Croft et al. 1998), hence the bias is well-defined (i.e. non-stochastic, to borrow a term from galaxy survey studies). However, by the present epoch, many baryons have collapsed into galaxies or been shock heated on filaments to warm-hot temperatures (Cen & Ostriker 1999; Davé et al. 2001), hence the relationship between Lyα absorption and the underlying mass distribution becomes more complex. The evolution of this bias is primarily governed by the expansion of the universe and the strength of the photoionizing background, the latter being the largest uncertainty in modeling Lyα absorber properties at present. Hence specifying, or better yet measuring, the evolution of this bias allows us construct a complete model of the Lyα forest.

In these proceedings we use simulations to investigate whether it is possible to constrain the evolution of Lyα absorption bias using only the observed correlation strength of Lyα absorption. Unfortunately, we will see that various physical effects make this a difficult task, at least given present observational capabilities. Nevertheless, the simulations make interesting predictions regarding the evolution of H I correlations from high to low redshift that are preliminarily in agreement with observations. Furthermore, O VI correlations show interesting trends that may help to unravel their association with Lyα absorbers, as well as constrain the growth of metals in the IGM.

Our simulation results are obtained from a PTreeSPH run having 128^3 gas and 128^3 dark matter particles in a $22.222h^{-1}$Mpc volume with a $5h^{-1}$kpc softening length. Our cosmological model is ΛCDM ($\Omega_m = 0.4$) with $\Omega_b = 0.02h^{-2}$, $\sigma_8 = 0.8$ and $h = 0.65$. At $z = 2, 1, 0$ we extract and analyze 400 spectra along random lines of sight through the volume. We add Gaussian noise of $S/N = 25$ to each 3 km/s pixel. Lines are identified and fit using AutoVP (Davé et al. 1997). Note that the total redshift path lengths at $z = 2, 1, 0$ are $\Delta z = 10.0, 5.8, 3.0$, respectively.

1. Pixel Correlations

In bottom-up hierarchical structure formation models, larger overdensities are more strongly correlated. In Figure 1 (left panel) we show how this relationship is manifested along one-dimensional redshift-space lines of sight through our simulation. We compute the excess number of pairs of pixels having densities (normalized to the cosmic mean) in the ranges typical of the Lyα forest, relative to a randomly distributed set of such pixels. Despite smearing by peculiar velocities, higher overdensities are still more strongly correlated, though in velocity-space the correlation length is only ~ 100 km/s. Note that the correlation *length* does not increase with density, contrary to what one finds in large-scale structure studies where e.g. the correlation length of clusters is higher than that of galaxies. Also, it is evident that the density correlation doesn't change from $z = 2 \rightarrow 0$, indicating stable clustering of Lyα forest structures.

At high redshift, the density is tightly correlated with the optical depth of Lyα absorption. Hence we would expect that Lyα optical depths would reflect correlations in the density. The evolution of such correlations would then, in principle, reflect the evolution of bias for a particular optical depth, since the density correlations are not evolving. The right panel of Figure 1 shows the correlations for pixels with optical depths $\tau > 0.125, 0.5, 2$. According to Cen et al. (1998), this measure most accurately reflects the underlying matter correlation, at least at $z = 3$. Note that here we are using the noise-added spectra, with the optical depth computed by inverting the flux, so the τ limits are actually flux limits of $F < 0.88, 0.61, 0.14$, respectively.

Figure 1 (right panel) shows that the flux correlations indeed show similar trends as density correlations at $z = 2$ and 1, but by $z = 0$ the optical depth limits do not clearly delineate density cuts. Furthermore, even from $z = 2 \rightarrow 1$ the correlation strength (for $\Delta v < 100$ km/s) has evolved very little, despite a comparatively large evolution in the photoionizing background that governs the bias (see e.g. Figure 7 in Davé & Tripp 2001). At $z = 0$, there is even a significant *anti-correlation* for $\tau > 2$ pixels, until $\Delta v < 100$ km/s. Thus, disappointingly, it appears that the pixel flux (or optical depth) correlations do not straightforwardly trace the evolution of the Lyα forest bias.

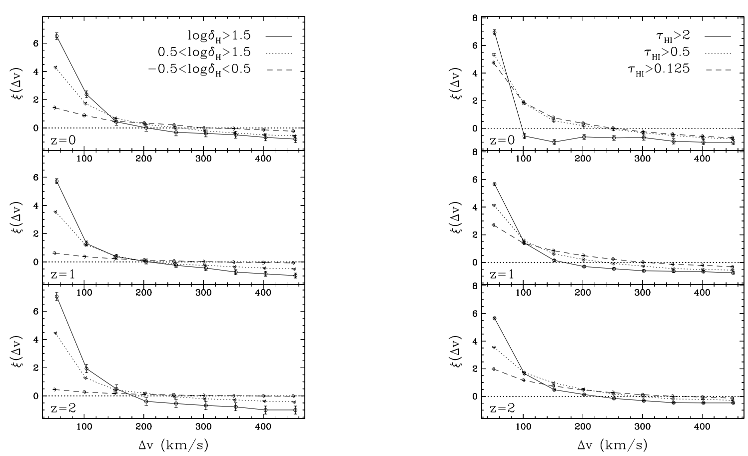

Figure 1 – *Left panel:* Line-of-sight density correlations at $z = 0, 1, 2$ for pixels in the range of $-0.5 < \log \rho/\bar{\rho} < 0.5$, $0.5 < \log \rho/\bar{\rho} < 1.5$, and $\log \rho/\bar{\rho} > 1.5$. *Right panel:* Line-of-sight correlations of pixels with H I optical depth $\tau > 0.125, 0.5, 2$.

2. Line Correlations

The canonical method for studying Lyα absorbers is by profile-fitting individual features. At high redshifts, studies indicate that Lyα lines are uncorrelated for $N_{\rm HI} \lesssim 10^{14}{\rm cm}^{-2}$. In these proceedings, low-redshift STIS spectra of Tripp et al. and Williger et al. show significant excess correlations of H I lines over a random distribution out to 250−300 km/s, for absorbers with $N_{\rm HI} \gtrsim 10^{13.6}{\rm cm}^{-2}$. The implication is that the correlation strength at this column density has increased with time, which is (qualitatively) expected from simulations since a given column density absorber is associated with higher overdensities at lower redshifts (Davé et al. 1999). Conversely, a poster by Heap et al. indicates no significant absorber correlations in a sightline towards 3C273 ($z_{\rm em} = 0.156$), where the typical absorber has a lower column density ($N_{\rm HI} \sim 10^{13}{\rm cm}^{-2}$). These results lend broad support to the bias evolution model given by simulations, but at present are insufficient to precisely constrain the bias evolution from high to low redshifts.

Figure 2 (left panel) shows our line correlation function for various column density limits, at $z = 0, 1, 2$. The line correlations at a given

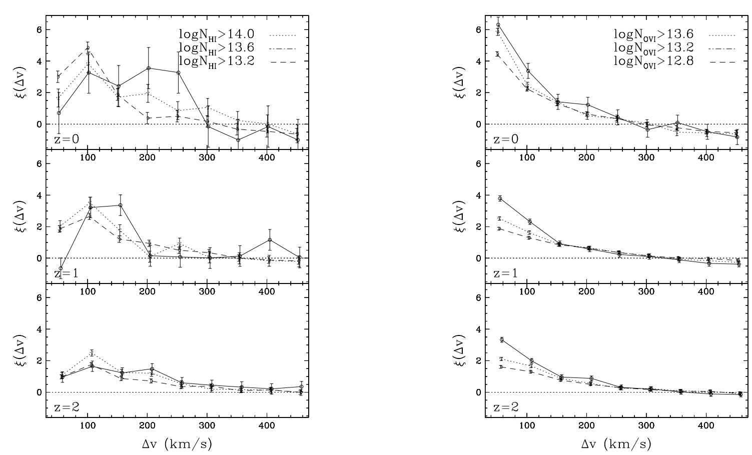

Figure 2 – *Left panel:* Line correlation function for Lyα at $z = 0, 1, 2$, with limits of $\log N_{\rm HI} > 13.2, 13.6, 14$. *Right panel:* Same for O VI absorbers, with limits of $\log N_{\rm OVI} > 12.8, 13.2, 13.6$. Note: Error bars shown are statistical, and do not include cosmic variance which is likely to dominate the error budget.

$N_{\rm HI}$ grow with time, in agreement with observations. At $z = 2$, virtually no correlations are seen in any column density range, while at $z = 0$ significant correlations are seen out to $\Delta v \approx 300$ km/s, for stronger lines. These trends are also in broad agreement with observations. Note also the interesting drop in correlation strength at $\Delta v \lesssim 50$ km/s; this is likely sensitive to line deblending algorithms, but may be an interesting regime for comparing simulations to observations if identical profile fitting routines are used.

Still, there seems to be no direct relationship between correlations computed from density cuts (cf. Figure 1) and from lines with column density cuts, meaning that while current simulations broadly reproduce observed line correlations, such correlations are also not simply related to the bias of the Lyα forest.

3. O VI Line Correlations

Recent observations suggest a significant number of O VI lines present in the local universe. Such lines may arise in collisionally ionized "warm-hot" gas or in very low density photoionized gas. Simulations roughly match the observed number density per unit redshift of lines by assuming [O/H]~ -1 and a quasar-dominated flux (e.g. Chen et al. 2002), with stronger absorbers tending to be collisionally ionized and the weaker absorbers photoionized (Cen et al. 2001, Fang & Bryan 2001). The correlation of O VI lines can, in principle, be used as a diagnostic to determine their origin, based on a comparison of their clustering strength with that of H I absorbers. A complication is that the metallicity and far-UV ionization conditions of the IGM are poorly determined.

We compute O VI line correlations from our simulation by assuming a Haardt & Madau (1996) ionizing background and a spatially-uniform metallicity that grows with time: [O/H]$= -2$ at $z = 2$, [O/H]$= -1.5$ at $z = 1$, and [O/H]$= -1$ at $z = 0$. These assumptions are reasonable but fairly arbitrary, as observational constraints are poor (see Prochaska, these proceedings, for a review). We also extract spectra with only O VI absorption, neglecting the real-world complication of blending with H I.

Figure 2 (right panel) shows the resulting O VI correlation function based on these assumptions. It is clear that stronger O VI lines are more strongly correlated, particularly at $z = 1$ and 2. This indicates that many of these O VI lines are photoionized, because collisionally ionized absorbers should have their column density virtually uncorrelated with density. At $z = 0$, this is not so clear, indicating more lines at these column densities may be collisionally ionized. Furthermore, the correlations of these lines are fairly strong out to hundreds of km/s, indicating that O VI absorption is mainly occuring in filaments. Finally, with the stated assumptions, the O VI line correlation strength does not increase significantly with redshift in comparison with that of H I.

At present there are insufficient numbers of O VI absorbers observed to test these simulation predictions. Upcoming observations with COS may alleviate this situation, though issues of blending with H I and uncertainties in ionization conditions will make interpretation difficult. In principle, a similar analysis could be applied to C IV absorbers; while not shown for lack of space, C IV also shows very little evolution in correlation strength (assuming an increasing metallicity with time), and even stronger correlations than O VI at all redshifts.

4. Conclusions

We have investigated various line-of-sight autocorrelation measures for weak H I and O VI absorption in the IGM. Correlations can in principle associate a given optical depth or column density with underlying physical densities within a hierarchical framework, thereby constraining the "bias" of the Lyα forest. Unfortunately, the increasingly complex physics associated with the low-redshift IGM make this untenable at present. Nevertheless, predictions of line correlations from hydrodynamic simulations broadly agree with observations, showing a growing correlation strength with time at fixed a fixed column density, and significant correlations out to ~ 300 km/s for strong lines at $z \sim 0$. More careful comparisons and improved observations will be needed to quantitatively assess any discrepancies, but for now it appears that the bias evolution model forwarded by structure formation scenarios for the Lyα forest is in agreement with observations.

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